



In-Bore Liquid Injection for Barrel Cooling: Comparison of Liquid and Solid Additives Using Constant Breach Pressure Ideal Gun Calculations

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In-Bore Liquid Injection for Barrel Cooling: Comparison of Liquid and Solid Additives Using Constant Breach Pressure Ideal Gun Calculations

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Abstract

A new concept for reducing gun tube wear through the injection of a liquid as a shield in the wall boundary regions of a gun tube is proposed. In this new concept, the liquid is injected and largely remains as a film on the bore surface, thereby acting as a thermal shield in the wall boundary layer region. Ballistic performance is assessed using constant breech pressure (CBP) ideal gun calculations for liquid additives to high-performance solid propellant formulations. These calculations give limiting values for projectile muzzle kinetic energy (KE), assuming complete mixing of the liquid additive and the solid propellant. This is a worst-case scenario for the new concept to reduce gun barrel heating. The CBP calculations of representative gun systems provide a comparison of 3 liquids and 10 solid additives, based on increased muzzle velocity and reduced temperature of the combustion products. The CBP calculations demonstrate that, even if total mixing occurs, liquid additives compare favorably with recently studied solid propellant additives. The CBP results, with as little as 4% liquid additive, indicate a potential to attain increased muzzle KE through the use of high flame-temperature and high-impetus solid propellants, without the penalty of increased temperature causing severe barrel erosion. They also indicate a potential for increased rate of firing because of the liquid's ability to reduce barrel heating. In either limit (i.e., total mixing or no mixing) the liquids studied, based on the CBP assumptions, emerge as attractive and competitive alternatives to solid propellant additives.

Table of Contents

	<u>Page</u>
List of Figures	v
List of Tables	vii
1. Introduction	1
2. Description of the Proposed Gun	2
3. General Description of the Idealized CBP Gun	6
4. Calculation Methods	7
5. Idealized CBP Gun With Variable Thermochemistry	7
5.1 The Use of BLAKE	7
5.2 Description of the Problem	8
5.3 Method of Calculation	9
5.3.1 <i>State 1 - Initial</i>	9
5.3.2 <i>State 2 - Burnout</i>	9
5.3.3 <i>State 3 - Muzzle</i>	10
5.4 Solid and Liquid Additives	11
6. Propellant Parameters Used for the Calculation	11
7. Ballistic Parameters and Gun Description	14
8. Calculation Results	14
9. Discussion of the Bore Surface Temperature	19
10. Conclusion	20
11. References	21
Distribution List	23
Report Documentation Page	25

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List of Figures

<u>Figure</u>	<u>Page</u>
1. Schematic of the Conceptual Liquid-Cooled Gun	3
2. Coordinates for the CBP Gun	6
3. Method of Maintaining Constant Solid Volume Fraction for Liquid and Solid Additives	12
4. CBP Gun Results Using the ChemP Calculation Method and BAC85	15
5. CBP Gun Results Using the ConP Calculation Method and BAC85	15
6. Comparison of the Three Liquid Additives Studied With BAC85 Referenced to Baseline JA2 Using the ChemP Method	17
7. Amount of Water and Hydrogen Present at Muzzle for Ethanol and Water Additives	17
8. BAC76 and 10 Solid and 3 Liquid Additives Compared to Baseline JA2 Propellant	18

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List of Tables

<u>Table</u>	<u>Page</u>
1. Identification and Densities of the Solid Additives	2
2. Identification ETPE Propellant Components	11
3. Ballistic Parameters for the Two Gun Systems Studied	13

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1. Introduction

With ever-increasing demands for higher muzzle velocities and rates of fire, barrel erosion and barrel overheating have become significant problems in modern guns of various types. Higher muzzle velocities are obtained by increasing the operating pressures of the propellant gases and through the use of propellants with higher flame temperatures. The penalties associated with such improvements are increased barrel wall temperature and the attendant effects of increased erosion and bulk barrel temperature—all of which shorten the barrel service life and limit the rate of fire. Four different approaches have been tried in the past to find a solution to effectively reduce barrel heating and erosion, while maintaining desired muzzle velocities and rates of fire.

In the first approach, the bore of the barrel has been plated with chrome or some other hard refractory metal. However, such plating has a limited lifetime because it develops microcracks that cause peeling of the plated coating. A second approach involves the use of additive wear liners, such as dimethylsilicone, talc wax, or titanium dioxide wax. These additives coat the surface of the bore and thereby reduce heat transfer and chemical attack on the bore wall.

The third approach for erosion and wear reduction is believed to be the most effective conventional way to decrease heat transfer to the barrel wall. It involves the use of additives mixed with the propellant to lower the flame temperature significantly, while imparting only a modest penalty to propellant performance. These additives are generally less energetic than the main propellant material but generate lower molecular weight combustion products. Examples of such additives are given in Table 1. Another such additive is oxynitrotriazole, as described in U.S. Patent No. 5,034,072 [1].

The fourth approach, the practicality of which remains to be demonstrated, involves providing a liquid-cooling medium from the projectile itself. In this approach, a liquid-filled capsule at the rear of the projectile ejects liquid onto the surface of the barrel bore as the projectile is propelled down

Table 1. Identification and Densities of the Solid Additives

Abbreviation	Name	Density (g/cm ³)
NQ	nitroguanidine	1.712
TAGN	triaminoguanidinium nitrate	1.540
HZBTA	hydrazinium bitetrazolamine	1.650
UREA	urea	1.285
MENENA	N-methyl-betanitroxyethynitramine	1.525
CG	cyanoguanidine	1.385
TAZ	triaminoguanidinium azide	1.430
DADNH	1,6-diazido-2,5-dinitraza-hexane	1.605
DANPE	1,5-diazido-2-nitrazo-pentane	1.295
DHED	dihydrazine ethylenedinitramine	1.695

the barrel and as the capsule is squeezed by the pressure of the propellant. An example of this approach is described in U.S. Patent No. 4,203,364 [2].

2. Description of the Proposed Gun

A new approach (filed for patent at the U.S. patent office) for significantly reducing gun barrel erosion and bulk barrel temperature in solid propellant guns is now described. Like the fourth approach mentioned previously, this approach also utilizes a liquid coolant; but, here, the liquid is injected from a reservoir in the gun onto the entrance surfaces of the barrel bore. One embodiment of this approach is the conceptual liquid-cooled tank gun shown in Figure 1. In the conceptual gun, the liquid is injected from opposite directions through two passages, each extending tangentially relative to the bore axis. Tangential injection is preferred because it utilizes centrifugal force to spread the liquid coolant circumferentially around the curved wall of the bore. Like in the reverse

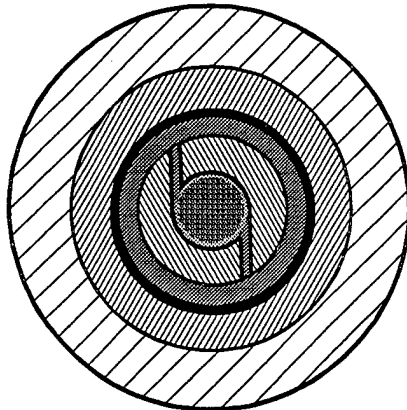
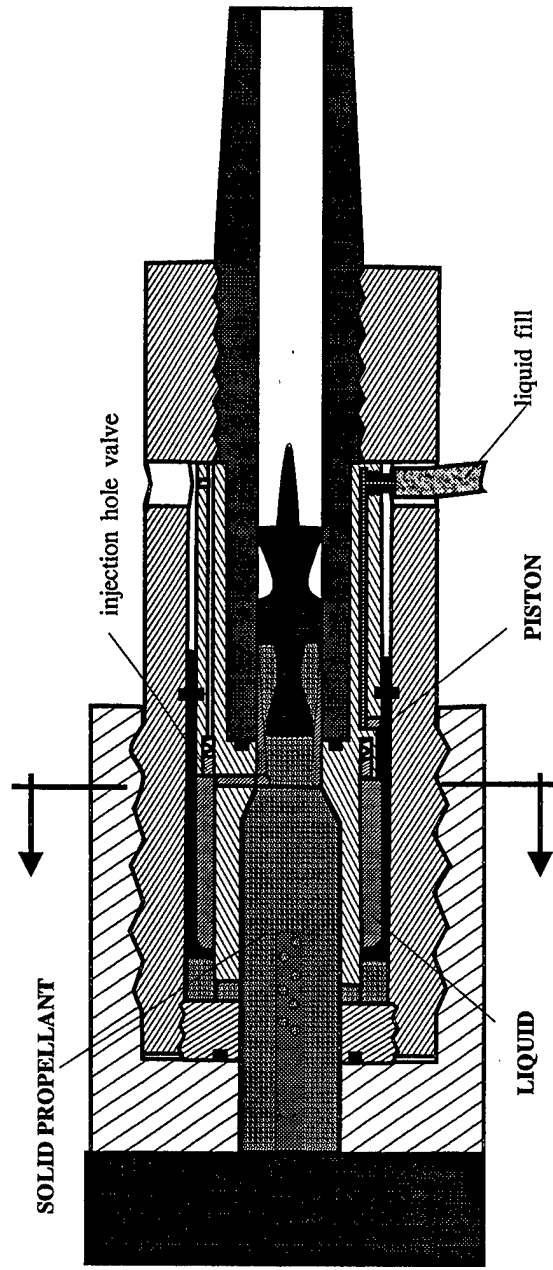


Figure 1. Schematic of the Conceptual Liquid-Cooled Gun.

annular gun concept of a regenerative liquid propellant gun (RLPG), the liquid coolant is fed to the injection passages from an annular liquid chamber formed between an annular injection piston and the wall of the gun block containing the ammunition (breech) chamber. One side of the piston head contacts the liquid, and the opposite side is exposed to a gas chamber that is fed with a portion of the propellant gases so that, upon firing of the ammunition, the piston is driven forward to inject the coolant into the bore at or immediately behind the base of the projectile as it starts down the bore of the gun barrel. The liquid is injected at a pressure higher than the pressure of the propelling gases because the area of the head in contact with the gas is substantially larger than the area of the head in contact with the liquid.

Because of the centrifugal force provided by the tangential injection, the injected liquid spreads out as thin film on the barrel wall. The hot gas flow that is pushing the projectile also pushes the liquid layer down the barrel on its bore wall, while vaporizing at least a portion of the liquid. Because the liquid and its vapor are in the boundary layer in contact with the bore wall, they follow the projectile down the barrel but at a lower speed than that of the projectile. The spreading liquid film and the vapor produced thereby shield the barrel from the main hot gas flow; also, the temperature of the barrel is lowered due to the cooler liquid and the conversion of at least a portion of the liquid, if not all, to vapor. This shielding effect, which is more pronounced at the entrance to the barrel bore where the film is thickest and where the most erosion would otherwise occur, enables the use of "hot" (highly energetic) propellants for increased muzzle velocity without the need to increase the pressure in the breech chamber. Without the shielding effect, such hot propellants cannot be used effectively without special means for cooling the barrel wall and external cooling will not provide sufficient temperature reduction to the inner wall where erosion takes place—severe erosion would be produced by the very hot combustion gases generated by the burning of these hot propellants. Thus, the conceptual gun can have an increased firing rate without the need for externally cooling the barrel. A similar liquid-cooling approach may also be considered for howitzers.

The present approach has numerous advantages over the prior-art technology discussed previously. Barrel chrome plating does not reduce heat transfer from the hot gases. Hence, the

increase in the bulk barrel temperature of plated barrels limits the sustained firing rates usable with such barrels. Furthermore, it is difficult and expensive to obtain uniform chrome plating in the bore of a barrel. Wear-reducing additives consume propellant charge space and limit the geometry of the charge. Propellant additives that lower flame temperature may appear to be promising, but they impart significant performance penalties and may shorten the shelf life of the main propellant and compromise its mechanical integrity. Liquid capsules at the rear of the projectile would significantly increase the cost of the ammunition and are believed to be impractical for most projectile designs. Even if practical, liquid capsules would be capable of cooling only around the moving projectile and would therefore be primarily effective well down the barrel length, not at the beginning of the barrel where erosion is most prominent.

Suitable coolant liquids for injection are water, methanol, ethanol, antifreeze solutions, and combinations thereof. The alcohols and their solutions are preferred because they are readily available, are easily vaporized, and have low freezing points and good cooling and protective characteristics. Water is less desirable because of the problem of freezing and because steam is a chemical corrosive. However, because these liquids do not increase the chemical energy available to the system, there is a penalty associated with the injection of these liquids into the bore of the gun barrel. The liquid is, in effect, a parasitic mass that is accelerated down the barrel by the gas flow, thereby consuming energy that otherwise would be available for transfer to the projectile as kinetic energy (KE).

On the other hand, because the hot combustion gas is cooled by the liquid, a hot burning propellant may be used that is more energetic than a baseline (standard) propellant so that the projectile actually may gain considerably more muzzle KE without exceeding the desirable baseline gas temperature at the wall of the bore. As a conservative example in support of this advantage, it may be assumed that the injected liquid instantly mixes with the propellant gas and immediately vaporizes and that this vapor reaches physical, chemical, and thermal equilibrium with the propellant gas. In other words, it is assumed that a portion of the system energy is used for completely vaporizing the liquid and for accelerating the mass of this vapor and the propellant, in the form of the resulting equilibrium composition, to the full velocity of the combustion gas. This is a

conservative case because, in reality, the liquid and its vapor will reside in the boundary wall layer, lag the projectile motion, and leave the core of the gas in the bore of the barrel unaffected. Here, the constant breech pressure (CBP) gun approximation is used to show that the barrel temperature is lowered with less reduction of the muzzle energy for selected liquid additives than if representative solid protecting additives were included along with propellant in the charge.

3. General Description of the Idealized CBP Gun

The characteristic features of this system are a constant pressure portion that lasts from the time the operating pressure is reached (shot-start) to the time the solid propellant is entirely consumed (burnout); this is followed by the reversible isentropic expansion of the gases until the end of the tube is reached (muzzle condition). The coordinates of the gun are shown in Figure 2.

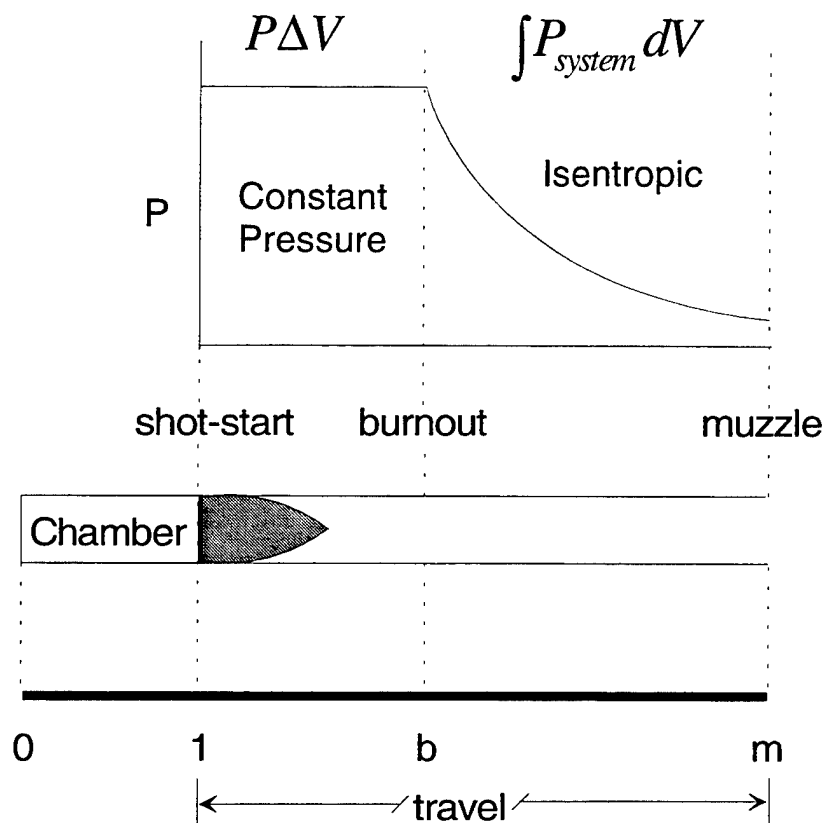


Figure 2. Coordinates for the CBP Gun.

4. Calculation Methods

Two calculation methods are used initially for the series; these are designated ChemP [3] and ConP. ConP is the traditional CONPRESS-type calculation [4]. The propellant characteristics used in the ConP calculation are quantified by impetus, specific heat ratio (γ), and Noble-Abel covolume (η). They are obtained from BLAKE [5] under closed-bomb conditions at a nominal, though arbitrary, loading density (l.d.) of 0.2 g/cm³. The chemistry is fixed (also termed frozen) over the ballistic cycle and changes only when a new calculation, with a different proportion of additive, is considered.

ChemP also uses BLAKE but does a full thermodynamic equilibrium calculation over the ballistic cycle. It is a rigorous calculation of the CBP gun that includes the effects of infinitely fast chemical kinetics (i.e., thermodynamic equilibrium). ChemP is generally the more conservative calculation [6]; it is also a self-consistent approach since it does not rely on a presumed loading density and thermodynamic state (l.d. = 0.2 g/cm³, adiabatic constant volume) as the ConP/CONPRESS approaches do. Consequently, ChemP is the method used in this study; ConP results are also included here for the first system studied since it is the more familiar method of calculation and a generally recognized point of reference.

Although the ChemP method has been discussed previously [3, 6], it is presented here again for clarification and convenience since it is not widely used.

5. Idealized CBP Gun With Variable Thermochemistry

The ChemP method of calculation utilizes a thermodynamic state description of the ballistic cycle. There are several steps that need to be considered to understand the process, but only three states (see sections 5.3.1–5.3.3) of the system need to be calculated.

5.1 The Use of BLAKE. BLAKE will be used to perform the calculations; however, the method relies on basic thermodynamic principles and is not tied in any way to BLAKE itself.

BLAKE is chosen because it allows for real gas effects and has the apparatus in place to calculate the designated states.

5.2 Description of the Problem. The process is adiabatic; so, for each step $Q = 0$. The breech pressure, also called the chamber pressure, is given and is determined by known operating parameters (design parameters) for the gun. A Lagrange gradient is assumed. The method of Lagrange is often used and is dealt with elsewhere [7].

The system here is the propellant and includes the total matter of any phase or composition that comprised the original unburnt propellant. The Lagrange gradient presumes that the solid is uniformly dispersed throughout the system volume. The use of the Lagrange gradient allows a partitioning of the total energy difference (i.e., between the initial state [unburnt propellant] and the final state [muzzle]) in the form of work done by the system that results in an increase of KE of the projectile and propellant. Strictly speaking, the total system energy, E , includes the internal energy and the bulk KE of the propellant and combustion products:

$$E_{\text{system}} = U + KE_{\text{Propellant}}$$

From the perspective of the thermodynamic equilibrium code (BLAKE), however, bulk KE of the propellant is not treated as part of the system. The internal energy of the system, U , includes the thermal and chemical energy of the system but not any bulk KE of the projectile, $KE_{\text{Propellant}}$. Since BLAKE will only calculate the internal energy, U , the relationships that follow from the choice of the Lagrange gradient assumption are used to partition the change in internal energy, ΔU , between the KE of the combustion gases and the KE of projectile, that is,

$$\Delta U = KE_{\text{Propellant}} + KE_{\text{projectile}}$$

Thus, the change in internal energy of the system results in work on the surroundings, which manifests itself as KE (velocity) of the propellant and the projectile.

5.3 Method of Calculation. Only three thermodynamic states need to be calculated. Each of these states is now considered.

5.3.1 State 1 - Initial. For the initial state, the internal energy of the propellant must be known or calculated. The initial state of a propellant is usually at ambient conditions taken here to be $P = 0.1 \text{ MPa}$ and $T = 298.15 \text{ K}$. These are also the conditions for which the standard enthalpy of formation is tabulated. This is also the reference T and standard pressure for BLAKE's assigned energy scale, consequently, for condensed-phase propellants [8], $U \approx H = (\Delta H_f^\circ)_{298.15 \text{ K}}$. The mass-specific internal energy of the initial state, U_0 , can therefore be calculated from the tabulated molar heat of formation, $(\Delta H_f^\circ)_{298.15 \text{ K}}$, the proportions of the components, the chemical formulas, and atomic weights.

5.3.2 State 2 - Burnout. The energy of the state at burnout, U_b , is calculated from the internal energy of the propellant and the mass specific work, W , done along the constant pressure path that is specified as a design parameter of the gun. Identification of this state is the key to performing the calculation. U_b is the initial energy less the work done:

$$U_b = U_0 - W.$$

For the total work done at constant pressure

$$m_c = P(m_c V_{0b} - V_C).$$

Here, V_C is the volume of the chamber, V_{0b} is the mass specific volume at burnout, and m_c is the mass of the charge (the propellant).

For the mass specific work

$$W = P(V_{0b} - V_{0c}),$$

where

$$V_{0c} = V_C/m_c.$$

Using the relationship

$$U_b = H_b - PV_{0b},$$

$$H_b - PV_{0b} = U_0 - PV_{0b} + PV_{0c},$$

$$H_b = U_0 + PV_{0c},$$

or

$$H_b = U_0 + P V_c/m_c.$$

Thus, the thermodynamic state at burnout is fully specified by the operating pressure and the enthalpy at burnout as indicated, where U_0 (the initial internal energy), P (the operating pressure), V_c (the chamber volume), and m_c (the charge mass) are all known design parameters. A calculation of the thermodynamic state at burnout provides values for the other thermodynamic variables, of which the entropy at burnout, S_b , is now utilized in the calculation of the state at muzzle.

5.3.3 State 3 - Muzzle. From the state at burnout, a reversible adiabatic expansion takes place to the muzzle. For a reversible expansion, $dS = \delta Q_{rev}/T$. Since the process is adiabatic, $\delta Q_{rev} = 0$ and the expansion proceeds along a constant entropy path (i.e., the entropy at burnout S_b equals the entropy at muzzle S_m). This is easily calculated by BLAKE using the value of the entropy at burnout, holding it constant, and going from the specific volume at burnout to the specific volume at muzzle, which can be calculated from the design parameters; that is, at muzzle

$$V_m = V_{Total}/m_c,$$

where V_{Total} , the total volume, is the sum of the chamber and tube volume:

$$V_{Total} = V_{chamber} + V_{tube}.$$

Thus, the desired value of the energy at muzzle is calculated from the known thermodynamic state at muzzle characterized by V_{Total} and $S_m = S_b$, and S_b is known from the state at burnout that is characterized by the known specified constant space mean pressure, P , and the derived value of H_b . Details of a calculation of this method using BLAKE are given in Kotlar [3].

5.4 Solid and Liquid Additives. Three liquid and 10 solid additives were included in this study. The three liquid additives selected are water, methanol and ethanol. The 10 solid additives used here are the same ones previously studied by Juhasz et al. [9]. The solid additive names, abbreviations, and densities (the densities for the solids are taken from the HUNTER program database [9]) used here are given in Table 1; details of the chemical structure of these additives are found in Juhasz et al. [9].

6. Propellant Parameters Used for the Calculation

Three solid propellants are used in the calculations. The base charge is JA2 (impetus = 1139.7 J/g, $\gamma = 1.2256$, $\eta = 0.993 \text{ g/cm}^2$, l.d. = 0.2 g/cm²). Two energetic thermoplastic elastomer (ETPE) formulations were studied: (1) BAC85 and (2) BAC76 (called PAP-1 in Juhasz et al. [10]); the components of these formulations are identified in Table 2. The designation BACxx represents a propellant formulation having the proportions BAMO/AMMO/CL-20 of xx% CL-20 and (100-xx)% of 1 part BAMO to 3 parts AMMO, all proportions by weight.

Table 2. Identification ETPE Propellant Components

Abbreviation	Name
BAMO	3,3-bis(azidomethyl)oxetane
AMMO	3-azidomethyl-3-methyl oxetane
CL-20	hexanitrohexaazaisowurtzitane

Each set of calculations presented here is done at constant solid volume fraction, as illustrated in Figure 3, which also schematically shows that the volume assigned to the solid remains fixed. This situation is appropriate for volume-limited charges, such as for a tank gun, where the loading density is close to the practically allowed maximum (but not necessarily the theoretical maximum based on propellant density alone). For the liquid additive, the mass and corresponding volume of the solid propellant are constant. For the case of solid additives, the mass and corresponding volume of the solid propellant are appropriately decreased, depending on the amount of solid additive, to ensure that the solid volume fraction is constant. The solid volume fraction is the volume of the solid propellant charge, excluding any porosity, divided by the chamber volume. Because the solids are in granular form, the charge is porous and the actual loading density of the solids is less than their intrinsic density. The solid volume fraction is also the ratio of the loading density of a propellant and its intrinsic density. For the baseline propellant, JA2, in the two cases studied here, the at loading density is 0.99 g/cm² JA2 for the comparison with BAC85 and 0.92 g/cm² JA2 for the comparison with BAC76; the intrinsic density for JA2 is 1.573 g/cm². This gives solid volume fractions of 0.629 and 0.584 for 0.99 g/cm² JA2 and 0.92 g/cm² JA2, respectively (and as indicated also in Table 3).

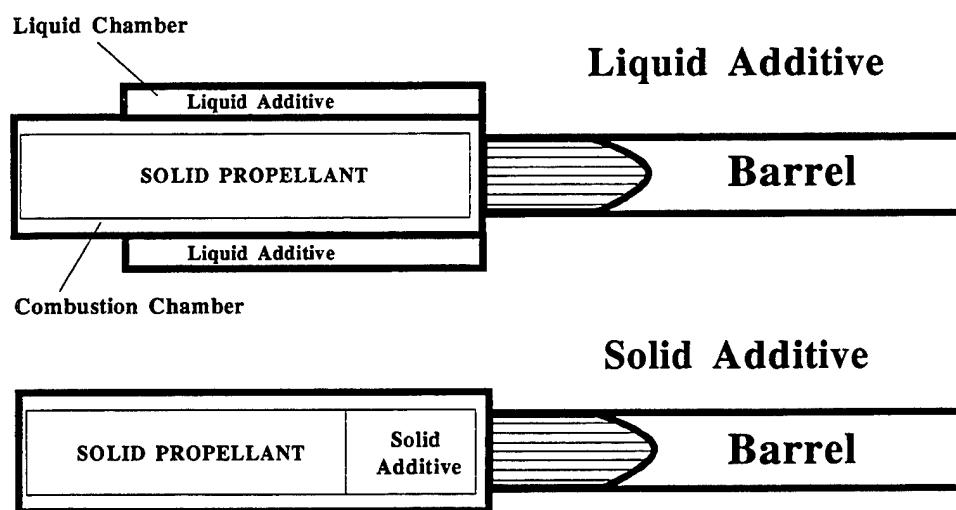


Figure 3. Method of Maintaining Constant Solid Volume Fraction for Liquid and Solid Additives.

Table 3. Ballistic Parameters for the Two Gun Systems Studied. Muzzle Results Are Given for the ChemP Calculation Method.

Propellant Studied (Density)	BAC85 (1.863 g/cm ³)	BAC76 (1.771 g/cm ³)
Baseline Propellant (Density)	JA2 (1.573 g/cm ³)	
Gun Type and Source	Notional [2]	Fielded [9]
Breech Pressure	575 MPa	528.14 MPa
Charge Mass (Baseline)	9.5 kg	9.004 kg
Projectile Mass	11.4 kg	7.135 kg
Chamber Volume (Baseline)	9.559 liters	9.779 liters
Bore Diameter	120 mm	120.82 mm
Barrel Length (=travel)	4.75 m	4.75 m
Muzzle KE (JA2 Baseline)	13.17 MJ	10.98 MJ
Muzzle Velocity (JA2 Baseline)	1520 m/s	1755 m/s
Loading Density (JA2 Baseline)	0.99 g/cm ³	0.92 g/cm ³
Solid Volume Fraction	0.629	0.582

In the calculations, the solids' mass is calculated such that the solids' volume is a constant 0.629 or 0.584 of the combustion chamber volume. Because different solid additives have different densities, in the case of solid additives, the actual charge mass varies, depending on the additive. In the case of liquid additive, constant solid volume means that the original base charge is always used and the liquid mass is added to it; however, for the liquid additive, the combustion chamber volume is increased by the volume of the liquid, and this varies depending on the density of the liquid and the amount of the liquid added. Thus, each method treating the two kinds of additives, solid or liquid, has specific and differing advantages and disadvantages that result from the inherent physical properties of the additives. The liquid is added as an additional mass to the full propellant base charge and with an increase in the effective chamber volume. For the solid, the chamber volume does not increase but the volume (and therefore the mass) of the base propellant must be decreased to allow for the volume required by the solid additive.

7. Ballistic Parameters and Gun Description

Ballistic parameters for the two gun systems are given in Table 3. For the BAC85 propellant, the generalized 120-mm tank gun ballistic parameters proposed in Juhasz et al. [9] were adopted. For the BAC76 propellant, a fielded gun system described in the STAR report [11] is used. Since a measured muzzle velocity is available in the STAR report, this allows a check to be made of the calculated values of the muzzle velocity; this is done for the JA2 base charge only. For the ChemP and ConP calculation methods, ballistic ratios (\equiv measured muzzle velocity/calculated muzzle velocity) of 0.97 and 0.94, respectively, were obtained [6]. This demonstrates that the CBP calculations give a good approximation of the measured muzzle velocity for this fielded gun system.

8. Calculation Results

Calculations were performed using the traditional, fixed composition method of calculating the CBP gun problem, ConP, and the full thermochemical description of the ballistic cycle, ChemP, as described previously.

Because the premixing of various solid additives with the propellant is an alternative to injecting ethanol or other liquids in accordance with the invention, the effects of various solid additives to BAC85 are also shown in Figures 4 and 5. Shown in Figure 4 are the results of CBP calculations done with the ChemP method for the liquid additive ethanol and the 10 solid additives. For comparison, the results for the ConP method are shown in Figure 5 using the same scale for the axes. The results of the ballistic calculations are plotted in Figures 4 and 5 as the percent change in muzzle KE from the baseline energy vs. the change in gas temperature from the baseline temperature.

Two different index temperatures are chosen as the appropriate temperatures for the two methods. The temperature for the ConP calculation is the flame temperature at constant volume, adiabatic conditions, and l.d. = 0.2 g/cm² (BLAKE's GUN command), since this is the customary condition used to calculate the effective thermodynamic parameters. For the ChemP method, the

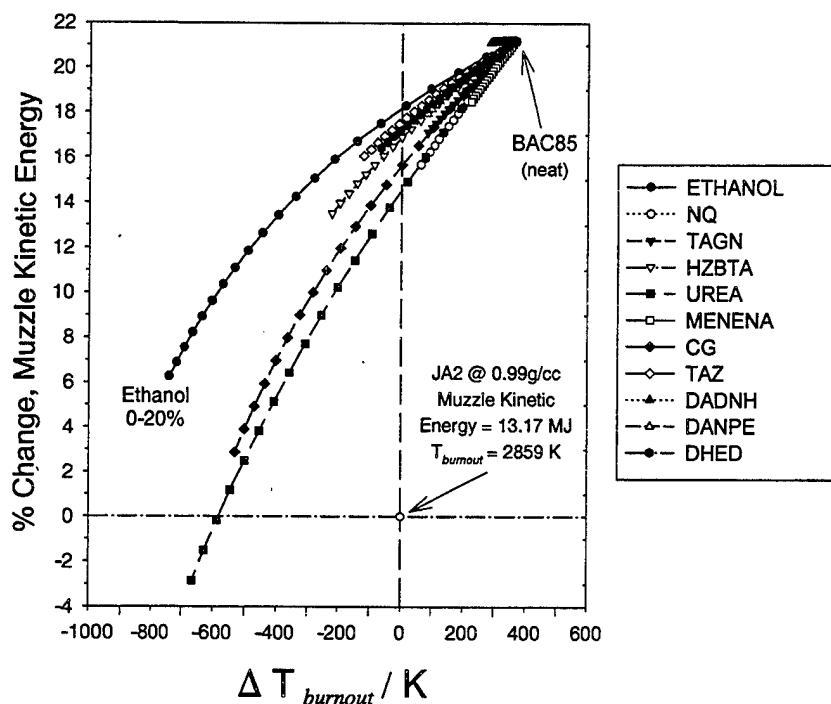


Figure 4. CPB Gun Results Using the ChemP Calculation Method and BAC85. Data Are at 1% Intervals of Additive by Weight.

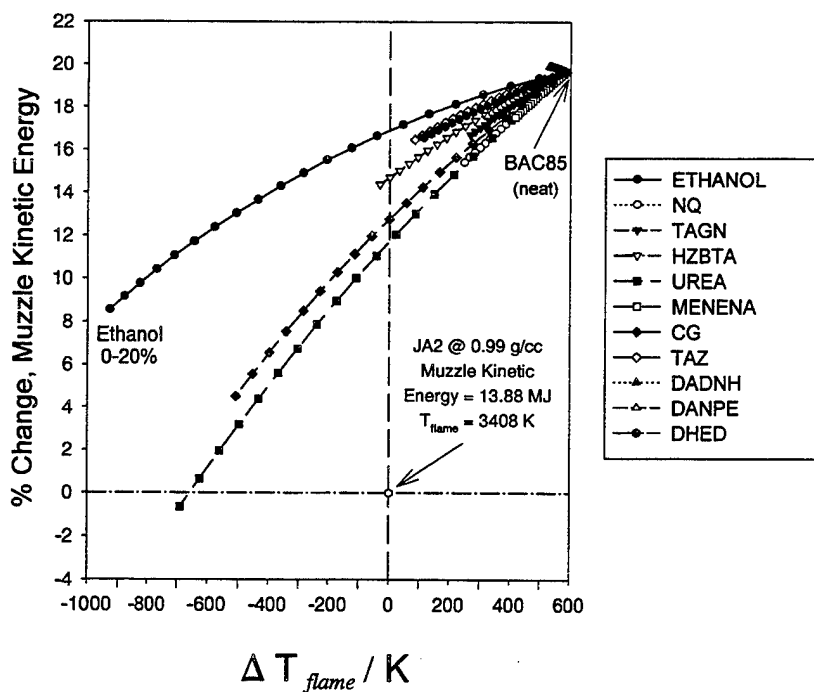


Figure 5. CPB Gun Results Using the ConP Calculation Method and BAC85.

temperature for the state at burnout is used, since it is the true temperature (within the scope of the ideal CBP gun description and full thermodynamic equilibrium) for this well-defined thermodynamic state of the ballistic cycle. Consequently, for the JA2 baseline, as indicated in Figures 4 and 5, $T_{burnout} = 2,859 \text{ K}$ and $T_{flame} = 3,408 \text{ K}$ (i.e., the index temperatures used here for ChemP and ConP, respectively, differ by 549 K). The quantity of direct interest, however, is the change in temperature resulting from the use of additives, and this is what is plotted. (The equivalent burnout temperature for the ConP approach can be calculated also, although it is not generally reported in ConP-type calculations. For the JA2 baseline in Figure 5, the ConP burnout temperature is 2,785 K; this is 74 K lower than the ChemP burnout temperature of 2,859 K.)

Also, each point on these and the subsequent plots represents the addition of 1% additive by weight. As discussed previously in reference to Figure 3, two different approaches are taken for treating the solid and liquid additives; this gives rise to two different interpretations of the percentages. For liquid additives, the percentage of liquid is based on the total solid charge, which does not change composition and of which the liquid is not considered to be a part. For the solid additives, the percentage of additive represents the proportion of additive in the total solid charge of which it does form a part.

These results show that it takes only 4% by weight of added liquid mass (ethanol, Figure 4) to cool the hotter combustion gas from burning BAC85 back to the baseline JA2 gas temperature, while still retaining over 80% of the gain in muzzle KE of the projectile. Thus increased performance is predicted for the same gas temperature as the original JA2 charge and, presumably without increased barrel erosion, to the extent that the gun tube erosion correlates with temperature. Even at the 20% liquid additive level (ethanol) a small performance enhance is indicated (6%) along with a large drop in the relative operating temperature (-800 K). This implies a regime where the lower operating temperature would permit higher rates of fire without excessive heating of the gun tube. Overall, the injected liquid performance is substantially better than that of any of the premixed solid additives. The three liquids as additives to BAC85 are shown for comparison in Figure 6; the ethanol results in Figure 6 are the same as those plotted in Figure 4. Figure 7 compares the quantities of water vapor and hydrogen at muzzle (using the ChemP method) for water and ethanol as the

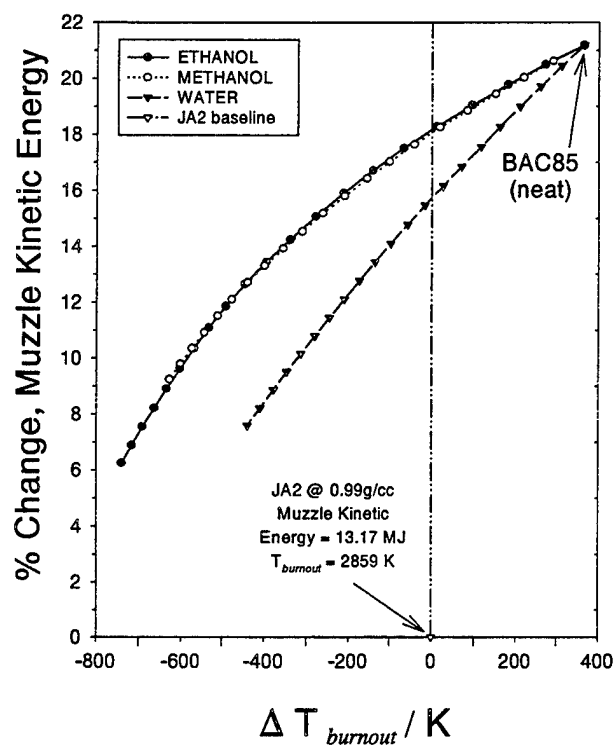


Figure 6. Comparison of the Three Liquid Additives Studied With BAC85 Referenced to Baseline JA2 Using the ChemP Method.

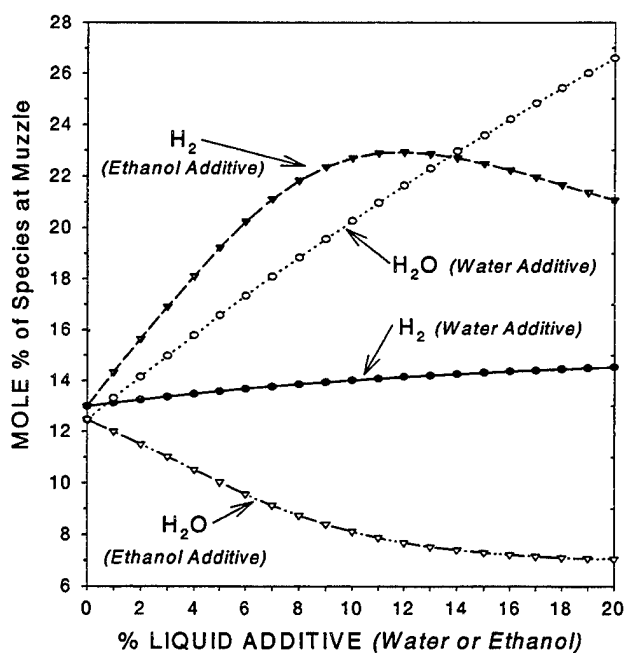


Figure 7. Amount of Water and Hydrogen Present at Muzzle for Ethanol and Water Additives.

additives. This illustrates that a significant factor in the superiority of ethanol over water as an additive is the formation of relatively large quantities of the low molecular weight hydrogen with ethanol additive, but the presence of large amounts of the higher molecular weight water vapor when water is the additive.

The complete set of 10 solid and 3 liquid additives is plotted in Figure 8 for the fielded gun system documented in the STAR report [11]. Qualitatively, the results for this system comparing BAC76 and JA2 are the same as those of the previous notional gun system in Figure 4 that compares BAC85 and JA2. In Figure 8, the drop in KE in the ethanol curve for 13–15% additive occurs when BLAKE predicts the formation of solid carbon during the adiabatic expansion part of the ballistic cycle. As more ethanol is added, BLAKE predicts that the onset of the formation of solid carbon takes place during the constant pressure part of the expansion; at this point, 16% ethanol added, the predicted KE returns to the previous trend.

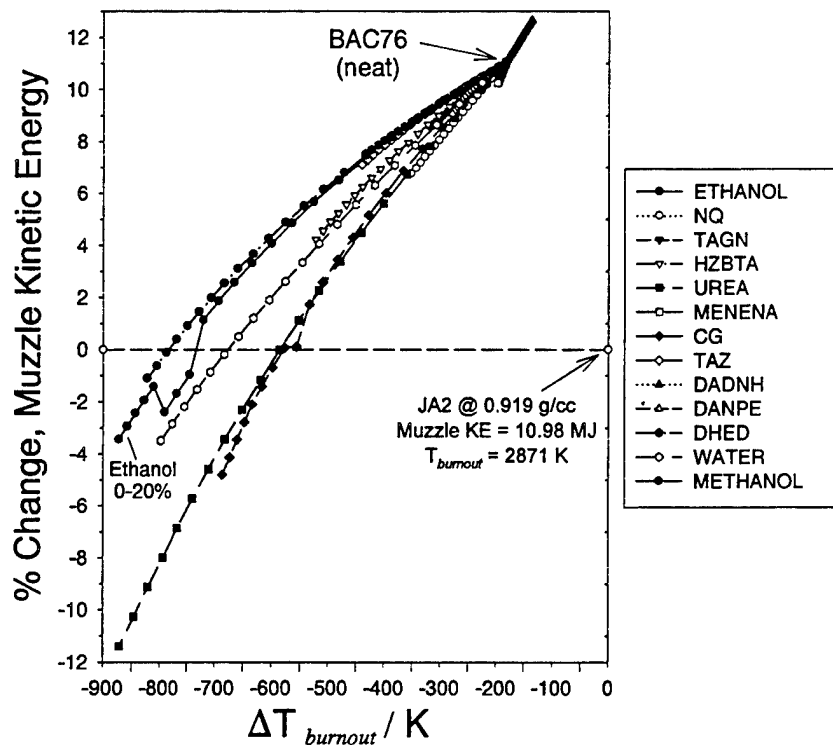


Figure 8. BAC76 and 10 Solid and 3 Liquid Additives Compared to Baseline JA2 Propellant.

9. Discussion of the Bore Surface Temperature

Because of uncertainties in the physics of the heat and mass transfer processes involved in the proposed liquid injection concept, an estimate of the bore surface temperature is not calculated. Presumably, variations in combustion gas composition for the cases studied (at a preset breech pressure) will affect the bore surface temperature significantly less than the core gas flow temperature. Hence, it is assumed that, if by injecting the liquid into a hot propellant, the gas temperature is reduced to its baseline (i.e., JA2 propellant without injection), and then the erosion is therefore also reduced to its baseline. This of course applies to the total-mixing assumption that was considered as a worst-case scenario with respect to bore surface temperature. However, the proposed liquid injection is believed to result in a liquid insulating layer on the barrel wall. Analysis of the effectiveness of a liquid layer in reducing the bore surface temperature was done by Wren and Oberle [12], with respect to an electrothermal gun with vaporized liquid as the working fluid. Wren and Oberle calculated that, for a 120-mm gun with 8 kg of JA2 propellant at 483 MPa maximum breech pressure, the bore surface temperature near the shot start is about 1,030 K. (Our baseline gun operates at 575 MPa with 9.5 kg JA6.) For the same gun with 6.5 kg of working fluid, whose temperature is about 570 K higher than the JA2 flame temperature, the surface temperature will be over 1,310 K in the absence of liquid layer but the temperature will resort to the 1,030-K level if it is assumed that a 5-mm layer of water coats the surface. Furthermore, Wren and Oberle calculated that, if 15% (0.97 kg) of the working fluid forms a water film on the wall, the bore surface will not exceed 1,030 K (the JA2 baseline) at any point along the bore. By analogy, with the absence of any mixing, approximately 1 kg of water injected as wall film into BAC85 combustion gas (the equivalent of the working fluid) will keep the barrel surface temperature at its baseline value. In the case study (see Table 3), this amounts to about 10% water additive by weight. Yet, the total mixing calculation shown in Figure 6 indicates that about 8% water suffices to retain the baseline core gas temperature. Consequently, with respect to the barrel surface temperature, there is little difference whether the liquid mixes or not. Furthermore, it is likely that the liquid-layer heat-transfer analysis conducted by Wren and Oberle overestimates the amount of liquid needed, since it does not take into account the liquid layer acting as a heat sink as it vaporizes along the barrel.

10. Conclusion

The CBP calculations of representative gun systems provide a comparison of 3 liquids (water, methanol, ethanol) and 10 solid additives, based on increased muzzle velocity (KE) and reduced temperature of the combustion products. Bearing in mind that the calculations are overly conservative with respect to the liquid injection case but not the solid additive cases, the superiority of liquid injection, according to the invention, is even more striking. In reality, with liquid injection, the boundary layer on the inner surface of the barrel will be far cooler than with any of the additives because additive cooling is a bulk process throughout the breech chamber, while the liquid cooling is a boundary layer process in a thin film. Ballistic calculations with water as the injected liquid indicate that, for the same liquid percentage, there is a greater performance penalty with water than with ethanol. The reason for this, in part, is that ethanol generates hydrogen that lowers the average molecular weight of the propelling gases, whereas water generates water vapor that is heavier than hydrogen. In other words, the lower the average molecular weight of the propelling gas and vapor mixture, the better the performance achieved by liquid injection.

It was found through the CBP calculations that, even if total mixing occurs, liquid additives in as low as a 4% by weight level (ethanol) compare favorably with recently studied [9, 10] solid propellant additives. As such, they survey the potential to attain increased muzzle KE through the use of high flame-temperature/high-impetus solid propellants without the penalty of severe barrel erosion (4% liquid additive). They also indicate a potential for increased rate of firing because of the liquid's ability to reduce barrel heating (20% liquid additive). In either limit (i.e., total mixing or no mixing), the liquids studied, based on the CBP assumptions, emerge as attractive and competitive alternatives to solid propellant additives.

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